The processing of SiC–SiC ceramic matrix composites using a pulsed Nd-YAG laser

Part II *The effect of process variables*

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The machining of a composite material consisting of silicon carbide (SiC) fibres in a chemical-vapour-infiltrated SiC matrix has been investigated using a 400 W pulsed Nd-doped yttrium aluminium garnet laser. Part I of this work reported the findings of investigating the influence of the laser pulse parameters, principally with respect to the material removal rate. In this, the analysis concentrates on the quality of the processed surface and considers the effect of processing variables such as the choice and pressure of assist gas and the point of focus of the incident laser beam. Scanning electron microscopy is used to assess the extent of the heat-affected zone and its impact on the structural integrity of the composite.

Throughout this study, comparison is made with related ceramic matrix composites (CMCs) that have been investigated. The intention is that, by determining the influential factors in each of the *specific* cases, observations may be made concerning the laser processing of CMC material systems in general.

1. Introduction

The last decade has seen an increasing emphasis on the development of ceramic matrix composite (CMC) systems, principally to overcome the limitations in terms of low fracture toughness and reliability presented by monolithic compositions whilst retaining their elevated-temperature properties. The choice of suitable fibres has been quite limited from the outset, with silicon carbide (SiC) exhibiting a clear advantage for most high-temperature structural applications. It is the development of matrix phases and the refinement of the interfacial chemistry that have resulted in a wide range of potential materials being investigated. These have included, owing to their relative ease of manufacture, materials that are more correctly referred to as *glass* matrix composites (GMCs) [1, 2] but extend to carefully tailored compositions that aim to maximize the mechanical potential of the composite [3, 4].

The principal aim of this investigation has been to study the effect of using a pulsed Nd-doped yttrium aluminium garnet (Nd-YAG) laser to cut various representative compositions of GMC and CMC. It is hoped that, by comparison of the results from the different materials, a more thorough understanding of the main factors involved may be gained.

In part I [5] of this work the results of varying the laser parameters used to process a SiC-fibre, chemical-vapour-infiltrated (CVI) SiC matrix CMC material were reported. The analysis concentrated on the material removal rates and the microscopic examination was concerned primarily with the geometry of the holes and cuts produced by the different conditions. The study continues with an investigation into the effects of various process parameters, with a greater significance being placed on the quality of the cut surface in terms of induced damage (microcracking and phase modification due to excessive heat input) and levels of redeposited material.

2. Material under examination

These tests continue the work on the SiC fibre–CVI SiC matrix composite material as specified fully in Part I of this work. The fibre used is proprietary Nicalon 201 grade SiC fibre, supplied in a sheet of cross-weave mat. Typically, 12 sheets of the cross-weave form a flat plaque 3 mm thick, which is subsequently infiltrated with a SiC matrix. The material produced by this method is relatively high in porosity but precise in chemical composition. The use of similar phases for both the matrix and the reinforcement has advantages in terms of relative thermal expansion coefficients and transmissivities, giving a composite with greater high-temperature capabilities than either of the previous glass–ceramic matrix materials.

3. Facilities and general laser configuration

Full details of the facilities used for these tests have been given in Part I of this paper. As a summary, the laser used is a Lumonics JK701 Nd-YAG instrument, used with the LD2 (low-divergence) resonator. A custom-built nozzle assembly allows rapid adjustment, when necessary, and the supply of assist gas to the process zone up to a maximum pressure of approximately 8 bar. A Unidex 400 computer numerical controller connected to a three-axis workstation permits 600 mm × 600 mm × 300 mm of accurate (± 0.2 mm over range) and programmable travel of the workpiece for duplicating test geometries on different specimens.

4. Test methodology

One of the principal aims of this work is to produce *comparative* data on the processing of related composite materials. In this way it is hoped that, in addition to determining the effect of adjusting the various lasing parameters when processing a specific composite, information may be gathered on the influence of the material chemistry and microstructure on the process.

Having investigated the influence of certain pulse parameters in Part I of this work, this next stage addresses how various processing conditions influence the quality of the laser-machined surface.

For trials of assist gas type and pressure a through-cut was machined to provide a surface for microscopic examination. The effect upon hole geometry of the height of the point of focus with respect to the surface of the material was examined by drilling a number of through-holes, which were subsequently sectioned and measured for entry and exit diameters.

To determine the highest speed where complete penetration of each plaque was achieved whilst minimizing the wastage of test material, a technique of accelerating the cut speed was used to identify approximate limits. This is possible using the computer numerically controlled table; an initial speed may be entered in the controlling programme, from which the speed of traverse is accelerated. It is then simply a matter of measuring the extent of the cut, and from that calculating the actual speed at the point at which full penetration fails. It should be noted, however, that this method may introduce an error associated with the effects of heat flow in the material. There is evidence that a build-up of heat in the process zone effectively assists the cutting process in steady-state conditions [6]; this test technique does not permit such a steady state to be established, and it is therefore possible that an erroneous maximum speed may be indicated. For this reason, many of the results (particularly on the thinnest material) were verified by performing a constant-speed cut.

For each of these tests, laser pulse parameters were selected to relate to the previous tests, so that legitimate comparison could be made between material removal rates and resulting surface quality and damage induced.

5. Laser processing results

5.1. Type and pressure of assist gas

The trials investigating the influence of the pressure and most notably the type of assist gas have shown the greatest differences between the three materials studied so far. In each case, four gases have been tried: nitrogen, argon, air and oxygen.

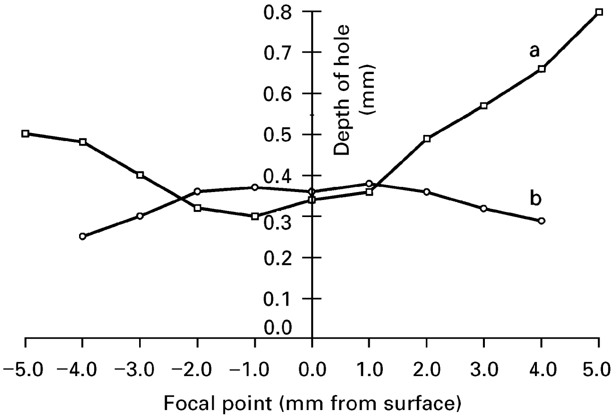

Figure 1 Focal point trials (plaque 3 mm thick, 5 bar gas assist). Curve a, entry hole diameter; curve b, exit hole diameter.

The initial work on the Pyrex matrix GMC [7, 8] showed that there was very little advantage to using a gas pressure higher than 5 bar in terms of surface quality (amount of redeposited material) in the case of drilled holes or maximum traverse speed when cutting. However, this material highlighted the significance of the choice of assist gas. When oxygen was used, there was a severe reaction with the silicate matrix phase, resulting in a great deal of "dross" being generated along the cut, which in some cases was sufficient to close the cut upon resolidification. This problem was largely avoided by the use of nitrogen or argon, and to a surprising degree by the use of air. It was concluded that the air was involved in an oxidative reaction with the vaporized material, and subsequently expelled, leaving a nitrogen-rich atmosphere only to react with the bulk material. In both the previous material cases, there was very little observable reaction with the SiC fibres.

5.2. Variation in focal point

Once again in the interests of a full comparison with the previous material trials, a set of holes was drilled in the SiC–SiC composite to investigate the effect of varying the point of focus of the laser above and below the material surface. This has yielded some interesting results in the GMC and glass-ceramic matrix composite (GCMC) materials [7–10], with possible implications for hole shaping. The pulse parameters used were 7.0 J pulse energy, 2.0 ms pulse width and 36 Hz pulse repetition rate, giving a peak power of 3.5 kW. The results are shown in Fig. 1.

5.3. Maximum cut speed

Trials to investigate the maximum speed at which the SiC–SiC composite could be laser cut for various material thicknesses have been performed. The results are presented in Fig. 2. Unlike the GMC and GCMC specimens, the samples used for the latest series of investigations have not been specially made plaques but have been cut from a component form.

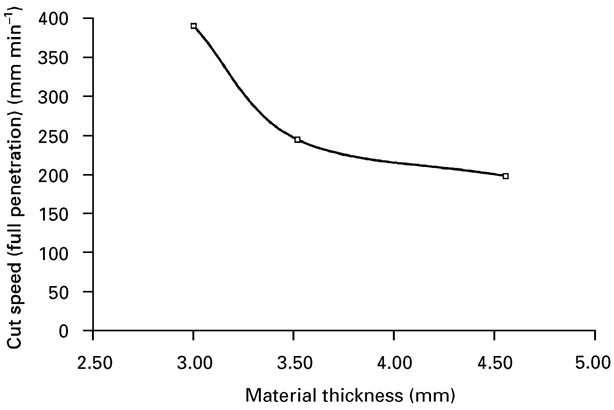

Figure 2 Maximum cut speed (3.5 kW) versus material thickness (5 bar N_2 gas assist).

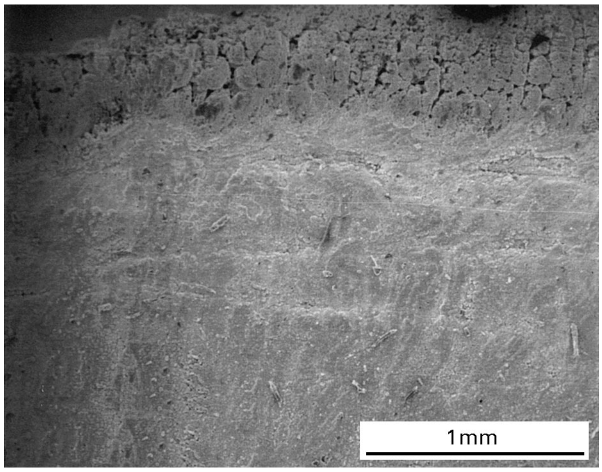

Figure 3 Cut surface produced at 150 mm min^{-1} (5 bar N_2 gas assist).

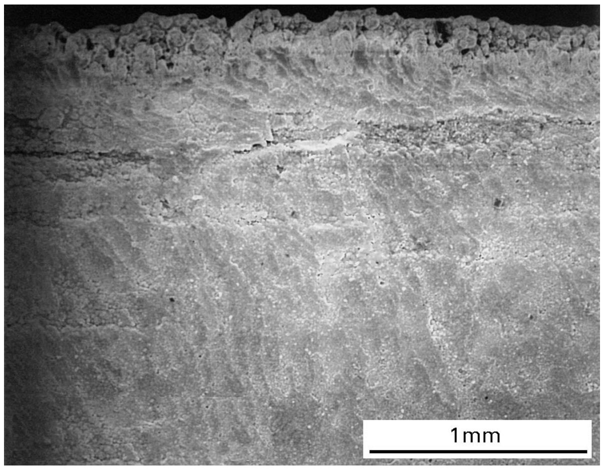

Figure 4 Cut surface produced at 150 mm min^{-1} (5 bar Ar gas assist).

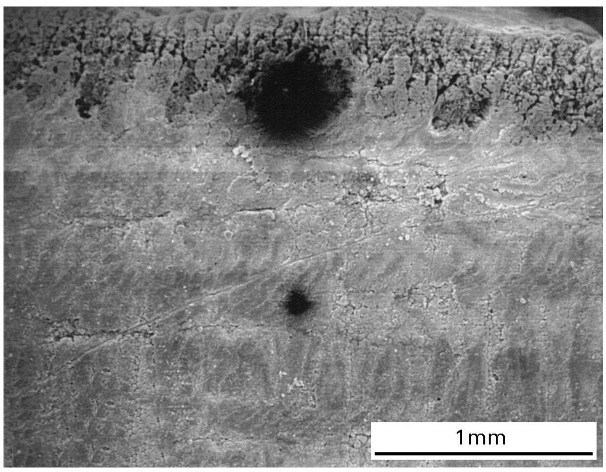

Figure 5 Cut surface produced at 150 mm min^{-1} (5 bar air gas assist).

Consequently, the number of thicknesses of material that could be tested were limited to the three sectional thicknesses of that component.

With reference to Fig. 2, the maximum cut speed is shown to be inversely related to the material thickness in common with the more substantial batch of data obtained from the preceding two materials. The trend is again approximately hyperbolic, the cut speed increasing dramatically with decreasing material thickness. It was suggested in the report on the magnesium-alumino-silicate (MAS) matrix material [9] that this may simply reflect the influence of heat transfer rates within the different thicknesses of material, as such factors are almost certainly a major consideration in this form of processing. In the absence of an exhaustive mathematical modelling of the heat flows, this must remain as speculation, but it is interesting to note that this feature is still prevalent in a composite that is as different in terms of thermal coupling as this. The maximum cut speed attained represents a 30% increase over the results from the MAS matrix material.

6. Scanning electron microscopy examination and discussion of results

6.1. Type of assist gas

Four gases, namely N_2, Ar, O_2 and air, each supplied at 5 bar were investigated to determine the effects if any upon the quality of the processed surface when using the laser to cut the material. As had already been found during the testing of the GMC material, the choice of assist gas had very little effect on the maximum speed of cut achievable.

Fig. 3 shows the surface of the cut at produced at 15 mm min^{-1} with N_2 gas assist at 5 bar. It may be seen that there is almost no evidence of oxidation, with very slight traces of silicate material evenly deposited over the entire cut surface. This may be expected to a large degree; the oxidation energy of SiC is high, combined with the absence of free oxygen prevailing in the nitrogen-washed area.

The results are very similar when the assist gas is changed to argon, as depicted in Fig. 4. The cut produced using air (Fig. 5) does exhibit a slightly heavier deposition of the silicate material at the top of the cut surface, and the more disrupted appearance of the general structure suggests that the environmental attack may be concentrated on the pure carbon interfacial layer on the SiC fibres. This would certainly be the most reactive species in the material if exposed to an oxidizing atmosphere at high temperatures. This

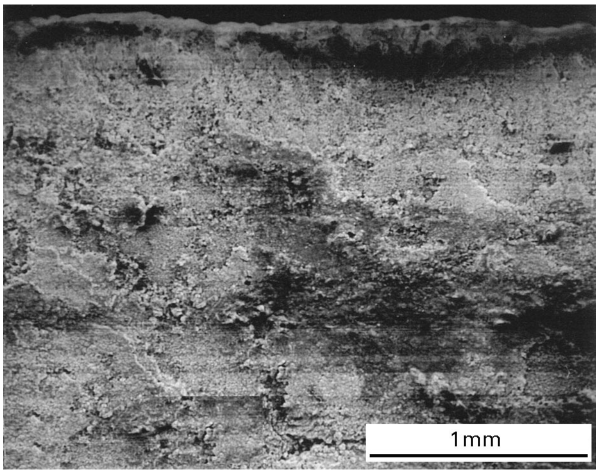

Figure 6 Cut surface produced at 150 mm min^{-1} (5 bar O_2 gas assist).

damaged region would seem to extend to approximately 0.5–0.75 mm depth of cut, below which the surface reverts to the cleaner undamaged appearance of the nitrogen and argon trials. Finally, the results obtained from using oxygen are shown in Fig. 6. In this case there is a more uniform presence of the silicate phase over the entire process surface although, even in this case, a comparison with the equivalent examples from the GMC and GCMC materials shows the oxidation to be slight.

It was noted when preparing the specimen for examination that the kerf width was noticeably smaller than in previous trials. It was suspected that the cuts either had not penetrated or had "healed" during the processing, but this was found not to be the case. Through-cuts with a width of less than 0.5 mm had been achieved in each case, with an absolute minimum of damage to the exposed surfaces.

6.2. Focal point trials

The examination of the series of defocusing trials enabled the entry and exit holes to be measured, the overall geometry of the holes checked (for instance to see whether the holes were indeed constantly tapered or whether they exhibited "barrelling"), and checked the quality of the hole bores (these were some of the few *through*-holes to be sectioned). Once again, the specimens give evidence of very clean holes, with very little deposited material either on the bore or around the entry hole. The variation in the through taper, as depicted graphically in Fig. 1, is shown in Fig. 7.

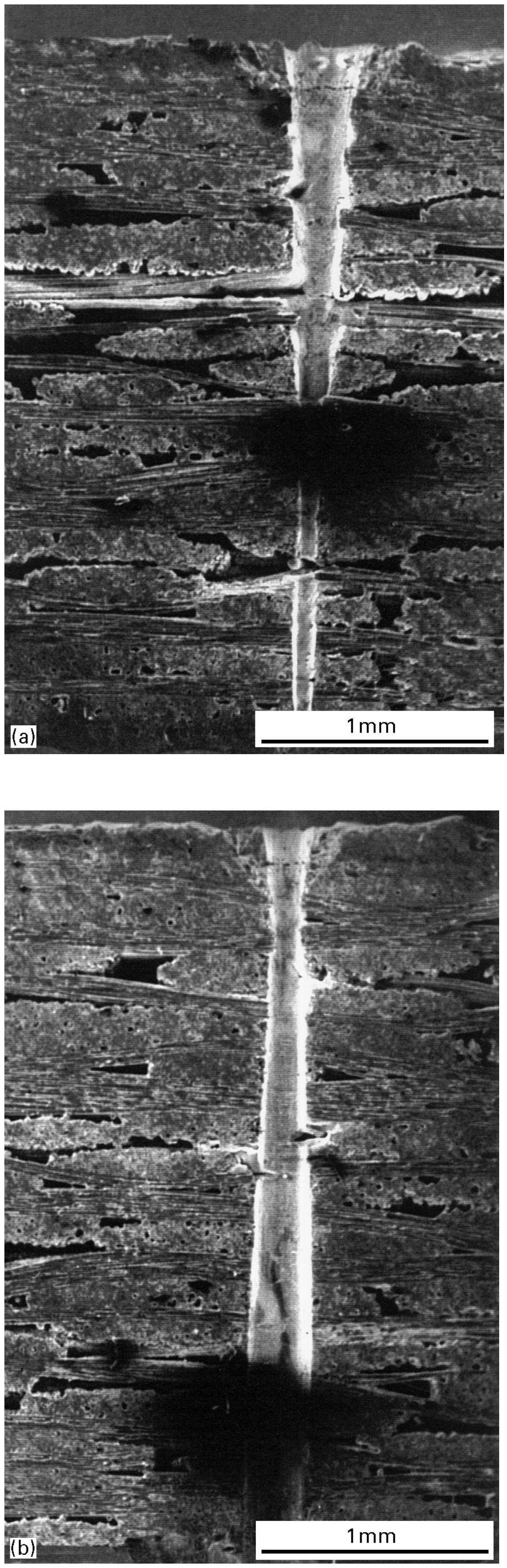

Figure 7 Defocusing trials: (a) with beam focused at a point 5 mm above the material surface; (b) with the beam focused at the material surface.

7. Summary

In reporting the YAG laser machining trials performed upon a SiC-fibre-reinforced, (CVI chemically vapour-deposited) SiC matrix composite, comparison has been made with similar trials on two glass–(glass–ceramic)-matrix, SiC fibre composites.

In both the drilled holes and the cutting, the SiC–SiC material exhibits a much cleaner, more "precise" processed surface. There is almost no silicate redeposited with nitrogen, argon or air gas assist, and very little when oxygen is used. This reflects the relatively low oxidation potential of SiC even at greatly elevated temperatures but does raise a question relating to the possible exposure of the chemically vapour-deposited, pure carbon interfacial layer. This is a very important feature of this composite's microstructure, influencing the mechanical properties by determining the adhesion between the fibres and the matrix. It is also extremely prone to oxidative degradation and so is effectively "sealed" from such atmospheres by a layer of lower-melting-point glass on the component surface. However, freshly cut surfaces expose the carbon, and it could be reasoned that a *complete* lack of redeposited silicate could result in severe damage when this surface is exposed to post-machining elevated temperatures.

The enhanced coupling achieved between the SiC–SiC composite material and the 1.06 μm laser emitted radiation is reflected in an increase in the maximum attainable cut speed of approximately 30% when compared with the MAS matrix GCMC [10].

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